Formation of Stable Sandy Beaches and Beach Erosion Control : A Methodology for Beach Erosion Control Using Headlands and Its Applications

TSUCHIYA, Yoshito

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By Yoshito TSUCHIYA

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Abstract

Many attempts have been made to control beach erosion throughout the world, but in the long term none have succeeded in stabilizing sandy beaches that are being eroded. Almost all the common countermeasures are of little use for stabilization as they cause beach profiles gradually to become steep. Some beautiful natural sandy beaches exist that are stable and in equilibrium for longshore sediment transport. The equation for a stable sandy beach is derived from the set of equations of continuity for beach change and longshore sediment transport under unsteady and nonuniform conditions, so that theoretical shoreline configurations can be obtained for both static and dynamic stable sandy beaches. The theoretical shoreline configurations of dynamic stable sandy beaches compare satisfactorily with those of actual sandy beaches and provide a theoretical background for the formation and existence of natural stable sandy beaches. A methodology for beach erosion control is proposed that is based on this theoretical background by which a series of stable beaches are formed from eroding sandy beaches. This method also is applied in relation to the large scale coastal behavior of sandy beaches. Its application under actual erosion situations has resulted in stabilization based on the establishment of well-formed stable sandy beaches. A brief description for further improvement of this methodology is also given.

1. Introduction

Acceleration of beach erosion throughout the world is now recognized as being due to the way humans have developed and utilized coastal zones and river basins. In some areas, beach erosion has also been accelerated because of a rise in sea level. Because of recent global warming and the resulting further rise in sea level, beach erosion will become an even more serious problem in the next century that must be solved in order to ensure land mass conservation. It is necessary to deliberate on what must be done to preserve coastlines as well as our conception of coastlines of the 21st century. Having been asked [1] by the Ministry of Construction of Japan to address these issues, I would like to begin with a short note on future coastlines.

It has been said that in the next century due to recent global warming both the scale of typhoons and their occurrences may increase and that a rise in sea level of more than about 50 cm may take place. Many years ago, Dr. Torahiko Terada, one of Japan's foremost scientists said, "Nature is faithful to her custom and experiences" and "Natural disasters are progressive in relation to civilization, they reoccur only once they have been forgotten." Repetition of abnormal natural forces may result in major catastrophes. The social environment produced in relation to human activities generally is irreversible, resulting in a linear increase in total entropy such that imbalances between nature and human activities are apt to be accelerated. Such imbalances may combine with abnormal natural forces that previously have been responsible for major disasters, and sometimes result in types of catastrophes that have never been experienced. Predictably, this tendency will become more marked in the years to come. Historical data on storm surges in Japan indicate that major storm surges will be more frequent within the first a few decades of the next century, which also may prove true for other natural phenomena that cause disasters. On the long-term time scale, such variations in the state of the weather and oceans are typical of ordinary variations in nature ; however, I think that if a disastrous event impinges on the results of recent human activities, it may well become an abnormal event such as has never been experienced before. The relation of the coastline dividing the land and the sea, therefore, must be discussed in relation to both its preservation and development.

1) **Nature and civilization** We human beings have developed sophisticated sciences and technologies over the millennia as well as have created spiritual cultures and higher civilizations. Oriental and western civilizations differ essentially in their basic understanding of nature[2]. Both natural sandy beaches and steep rocky shores show the beauty that waves have created over long periods of time. In the metaphorical sense, it can be said that there is "civilization" of waves that creates part of the majestic beauty of nature. The existence of human beings is of great significance to the harmony that nature and waves have created, as their own civilizations. In other words, a coexistent civilization must be created between human beings and nature by we, human beings who have great capability to change nature.

2) **Coastline preservation for the long term** Our country, which comprises the Japanese archipelago, is located in one of the most geoscientifically active areas of the earth, and this is the primary reason for the very beautiful coastlines found here. Imbalances between the long term creation process of nature and nature as reconstructed by humans exist, such as those resulting in beach collapse and erosion. In Japan, a coastal law has been enacted under which preservation of coastlines has been started, but difficult problems remain to be solved in the control of coastlines[3]. For example, it is clear that longshore sediment transport occurs within an area called a sedimentation cell and that this can not be controlled by the passage of laws. It must be kept in mind that nature maintains the continuity of sediment transport. When reformation of natural features by human beings takes place on a different time scale than that of nature, there is an inevitable reaction which may result in a major catastrophe.

In terms of coast preservation, the potential of this reaction has to be reduced as much as possible by ensuring that there is long-term preservation of coastlines against abnormal natural forces. It follows that a long-term methodology for the preservation of coasts must be established.

3) **Coastlines in greater harmony with nature** In various nations, and particularly in Japan, zoning of coastal areas has to be done for both the utilization and prevervation of coastlines.

So-called bay areas, in which natural features have been reconstructed effectively, may exist as well as sandy beaches that are in harmony with nature. However, it is better to zone coastal areas on the basis of the actual natural circumstances, such as longshore sediment transport, than for political reasons. It is necessary that the reconstruction of natural features by human beings should also be in harmony with the natural creation process. To counter rises in sea level and increases in the scale and frequency of typhoons that are caused by the global warming, a suitable long-term methodology for coast preservation has to established in this case too.

Many attempts have been made to control beach erosion in countries throughout the world[4], but in the long term none have succeeded in stabilizing sandy beaches that are being eroded. Almost all the common countermeasures; —sea dikes, groins, offshore breakwaters, mild-slope revetments and man-made reefs—are of little use for the stabilization of sandy beaches as they cause beach profiles gradually to become steep. Therefore, the reconstruction of sandy beaches so that they will be less affected hydraulically by a rise in sea level would be better for the preservation of coastlines than would be the construction of sea dikes and walls whose strength is dependent on the frontal depth of the water as well as the direct rise in sea level. Beach erosion in Japan has been increasing annually, and the tendency for erosion will become even more marked in the future. In many coastal areas, a great number of structures have been erected and, in general, they have protected the coastlines from severe beach erosion for more than thirty years. In certain coastal locations some have promoted beach collapse because of the direct influence of the structures themselves, and others have produced new complex problems related to coastal environments. The reformation of other natural sandy beaches must be based on new methodologies of long-term beach stabilization that reflect information gained from the effects of such previous countermeasures such as sea dikes, walls, and detached breakwaters, and so on.

Beach erosion in Japan, especially that seen in the reduction of river deltas because of a lack of or decrease in sediment source carried by rivers, must be considered over the long term taking into account large scale coastal behavior along the coast of a river delta as a creative process of nature. There are two possible methodologies: One is to recover the sediment from rivers thereby retaining the coastal river delta and the other is to establish a methodology which makes coastal stabilization possible for a coast that lacks a sediment supply. To create harmony with nature, coastlines must be stabilized and made more natural. Therefore, in envisioning Japanese coastlines of the next century as being in greater harmony with nature, I think we need to determine what will bring coastlines into this greater harmony that will lead to a new "civilization" in which there is beneficial coexistence between nature and human beings. I believe that coastal beauty that is based on the oriental concept of the inter-relatedness of humans and nature can be created.

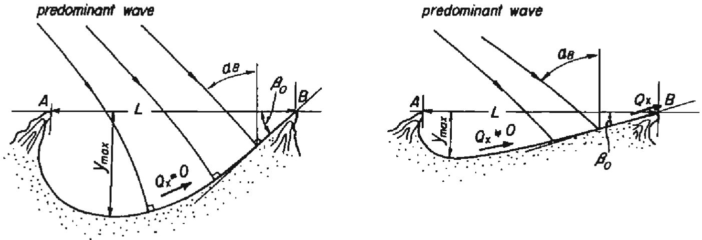
In 1960, Silvester[5] proposed a methodology for beach erosion control called "headland control", in which a series of static stable sandy beaches are formed. This is an essential methodology for beach erosion control; however, for practical application of our knowledge of nature, the theoretical or dynamic background of the formation of static stable sandy beaches must be known in order to determine the conditions necessary to their formation. Since I first learned of ζ-shaped bays from Silvester, I have conducted research to establish the theoretical background of the formation of natural stable sandy beaches. A stable sandy beach is formed under certain boundary conditions for beach change. The sandy beach is in either a static or dynamic equilibrium condition. When this theoretical background of the formation or existence of such stable sandy beaches is verified it can be used to derive a methodology for beach erosion control by headlands by which a series of stable sandy beaches can be formed to stabilize an eroding sandy beach.

From this point of view, I wish to propose a methodology of beach erosion control for coastal stabilization. First, two types of stable sandy beaches that are formed naturally and their geometry are briefly explained. Then, from the set of equations for longshore sediment transport and the equation for continuity of shoreline change, an equation for stable sandy beaches is derived. As the fundamental equation is a second-order ordinary differential equation, two boundary conditions at the upstream and downstream ends of longshore sediment transport are required to solve it, reflecting the fact that theoretically only two boundary conditions for shoreline change are required for the stabilization of a sandy beach. The configuration of stable sandy beaches, static and dynamic equilibrium beaches, are derived theoretically and compared with the configurations of actual sandy beaches. From the results of the application of the theoretical background of the formation of stable sandy beaches, a methodology is proposed for sandy beach stabilization, as well as for beach erosion control by headlands that are effective as boundary conditions. Application to the stabilization of eroding sandy beaches by establishing a series of stable sandy beaches is discussed in relation to the large scale behavior of sandy beaches. Three practical applications that have already been made and that is currently underway are described to show the applicability of the proposed methodology.

2. Formation of the Stable Sandy Beach : Theory of Its Existence and Geometry

2.1 Definition of natural stable sandy beaches and their configurations

There are many kinds of natural sandy beaches. Silvester[5),6)] was the first to focus on the sandy beach of a ζ-shaped bay bounded by two headlands. This type of sandy beach in a ζ-shaped bay is formed where there is no longshore transport of sediment while another type of sandy beach is formed where there is a constant rate of longshore sediment transport along the beach. As shown schematically in **Fig. 1**, Tsuchiya, Silvester and Shibano[7)] and Silvester, Tsuchiya and Shibano[8)] defined two types of natural sandy beaches that are in equilibrium



(a) Static stable sandy beach. (b) Dynamic stable sandy beach.

Fig. 1. Definition of stable sandy beaches and the notations used.

with the longshore sediment transport along them. One is a static stable sandy beach (better defined as a static equilibrium sandy beach) along which no longshore sediment transport occurs and where incident waves approach the shoreline normally through wave diffraction and refraction produced by the bottom topography and shoreline orientation. The second is a dynamic stable sandy beach (better defined as a dynamic equilibrium sandy beach) along which there is a constant rate of longshore sediment transport and where the incident waves obliquely approach the shoreline. Individual physical processes exist for static and dynamic stable beaches that must be considered within the entire scale of beach forms, the so-called large scale coastal behavior that is discussed in the section on the methodology for beach erosion control by headlands.

As stated previously, a natural static stable beach bounded by two headlands exists where there is no longshore sediment transport. There are two types of static stable sandy beaches: One has two headlands on which waves are incident normal to a line between the headlands. The other also is bounded by two headlands, but the waves are incident obliquely to this line called the "control line". For these sandy beaches clearly there is no peeling phenomenon of wave breaking—waves break simultaneously along the whole periphery. This means that there is no longshore transport of sediment along the beach. The definition of stable sandy beach in **Fig. 1** shows that the predominant wave is normally incident all along the beach, i. e., $\alpha_B = \beta_0$. Silvester[7] has shown from model experiments (**Fig. 2**) wherein in the static equilibrium condition the indentation ratio y_{max}/L (**Fig. 1**) is a function only of the angle β_0 between the down coast tangent and the control line. The ratio becomes large, resulting in a deeply curved beach, and tends to approach 0.5 when the beach is semi-circular and the angle becomes 90 degrees. Another type of sandy beach geometry can exist: a straight beach on which the predominant wave is normally incident.

As seen in **Fig. 3(a)**, a series of beautiful sandy beaches exist along the east coast of the Malay Peninsula where swells from the South China sea strike the beaches. These sandy beaches appear to be in equilibrium for longshore sediment transport and are dynamic stable

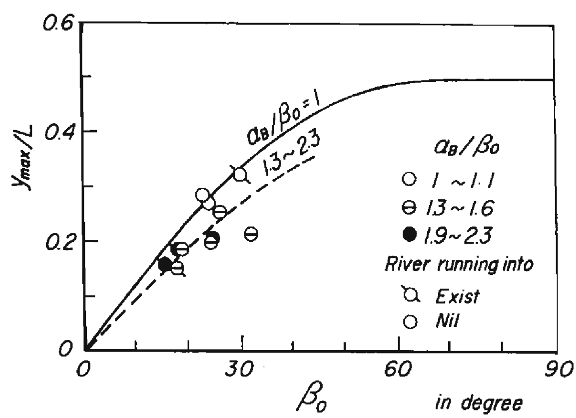
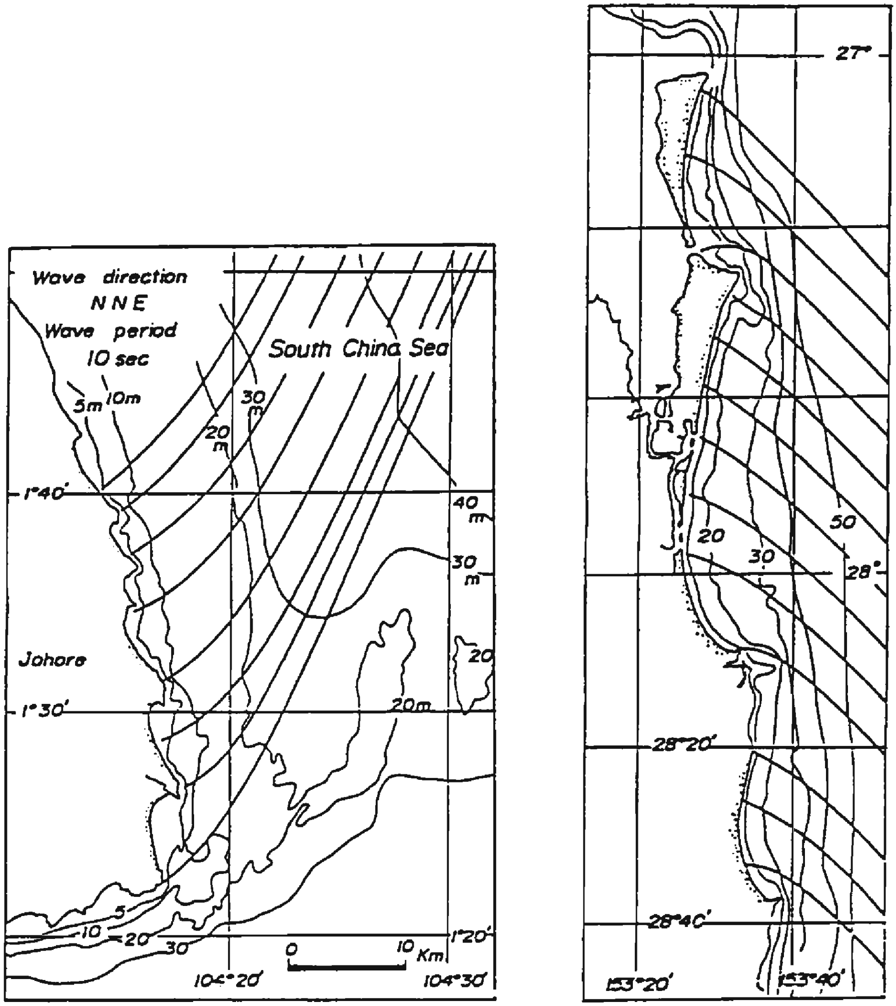


Fig. 2. Relationship between the incident wave angle and the indentation ratio of stable sandy beaches (Modified from Silvester's relation, 1976).



(a) The east coast of the Malay Peninsula. (b) The northeast coast of Australia.

Fig. 3. Examples of natural dynamic stable sandy beaches.

beaches. Another example can be seen in **Fig. 3(b)** which shows a series of well-formed sandy beaches on the northeast coast of Australia where swells from the southeast strike the beaches. A headland usually is present at both ends of dynamic stable sandy beaches along which there is a constant rate of longshore sediment transport. For the dynamic stable sandy beach, the indentation ratio is smaller than for static stable ones, showing a shallower bay.

2. 2 The governing equations of shoreline change and solutions for stable sandy beaches

There are two practical approaches : 1) numerical simulation of shoreline change to determine the background of the formation of stable sandy beaches, and 2) use of a theory for the formation of a stable sandy beach in terms of the equations governing shoreline change. The latter approach is used here, but the governing equation of longshore sediment transprot in the nonuniform condition also is needed. The equation of longshore sediment transport, therefore, is first derived theoretically. From the equations of longshore sediment transport and continuity for beach change, an equation of stable sandy beaches then is obtained to which solutions for the plane configuration of stable sandy beaches can be found.

Many procedures for modeling beach change have been reported, but the governing equations of shoreline change used are those for the continuity of beach change and longshore sediment transport in the uniform condition. It must be noted, however, that the phenomenon of longshore sediment transport along a sandy beach generally is nonuniform. Therefore, the general equation of longshore sediment transport is essential to obtain the equation for a stable sandy beach theoretically.

(1) The equation of longshore sediment transport in the nonuniform condition

So far an empirical or semiempirical formula for the total rate of longshore sediment transport has been used with the equation of continuity for predicting shoreline changes. A general equation of longshore sediment transport, however, is needed for a more precise formulation of shoreline change. By applying the boundary layer method to the equations of nearshore currents, Refaat and Tsuchiya[9] recently derived the equation of longshore current under the unsteady and nonuniform conditions. Using the coordinate system in which x and y_0(or y_b) respectively are taken in the longshore and offshore directions, the equation of longshore current is

$$\frac{\partial}{\partial t}(U_0 h_b^2)+\left(\frac{\alpha_3}{\alpha_1}\right)\frac{\partial}{\partial x}(U_0^2 h_b^2)=F(x)-\left(\frac{\alpha_3}{\alpha_1}\right)\frac{\gamma C_f c_b}{\pi}U_0 h_b \tag{1}$$

where

$$F(x)=\frac{\gamma^2 g h_b^2}{16\alpha_1}\left[\sin 2\alpha_b-2\cos^2\alpha_b\frac{\partial y_b}{\partial x}-(5\beta_1-6\beta_2+6\beta_3\sin^2\alpha_b)\frac{\partial h_b}{\partial x}\right.$$
$$\left.-2\beta_3 h_b\sin 2\alpha_b\frac{\partial \alpha_b}{\partial x}\right] \tag{2}$$

where y_b is the width of the breaker zone, U_0 is the nominal longshore current velocity that in practice can be taken as the velocity of longshore current at the breaker point U_b, and where α_b the breaker angle, h_b the breaker depth, g the acceleration of gravity, t the time and α_i and β_i (i=1, 2 and 3) are coefficients that are functions of $P=\pi Nm/\gamma\ C_f$ alone in which C_f is the bottom friction coefficient, N the lateral mixing coefficient in the surf zone, m the average beach slope, and γ the ratio of wave height to local water depth being 0.4, when the longshore current velocity of Longuet–Higgins[10] is applied. For practical purposes these can be taken to be constants. This equation, derived by assuming a similitude in longshore velocity distribution, is a one-dimensional equation of longshore current in the longshore direction where $F(x)$, derived from the longshore distribution of radiation stresses, corresponds to the hydraulic gradient in the open channel equation. For uniform conditions the equation becomes the Longuet–Higgins formulation for longshore current.

Tsuchiya[11] derived a theoretical formulation of longshore sediment transport for sediment transported by the longshore current on a sandy beach. The longshore current velocity of Longuet–Higgins[10] together with an expression for the average sediment concentration based on the total rate of sediment transport in the bed load, gives the total rate of longshore sediment transport ;

$$Q_x = C\left(\frac{\rho}{\sigma}\right) I(R,\ F_r)\ h_b^2\sqrt{gh_b}\sin 2\alpha_b \tag{3}$$

which can be transformed by using of the velocity of the longshore current U_b at the breaking point to

$$Q_x = \frac{c_0}{m}\left(\frac{\rho}{\sigma}\right) I(R,\ F_r)\ h_b^2 U_b \tag{3a}$$

where Q_x is the total rate of longshore sediment transport, c_0 and C are constants, σ/ρ is the specific gravity of the sediment, m the average beach slope, and h_b the breaking depth. When the value of F_r becomes very small corresponding to the field case, the value of $I(R,\ F_r)$ becomes nearly constant (0.3, in this case) and the total rate of longshore sediment transport is proportional to the wave power in terms of Eq. (2). The value, however, varies with F_r. When it becomes large, corresponding to the laboratory case, the total rate of longshore sediment transport depends on $I(R,\ F_r)$, and is not proportional to the wave power alone.

Inserting Eq. (3a) into Eq. (1) yields

$$\frac{\partial Q_x}{\partial t} + \frac{\alpha_2}{\alpha_1 k}\frac{\partial}{\partial x}\left(\frac{Q_x}{h_b}\right)^2 = \mathrm{k}F(x) - \frac{\alpha_3 \gamma\sqrt{g}\,C_f}{\alpha_1\sqrt{h_b}}\,Q_x \tag{4}$$

On the assumption that any small change in a shoreline is considered only when the breaker angle is assumed to be extremely small, Eq. (2) is approximated as

$$F(x) = \frac{\gamma^2 g h_b^2}{16\alpha_1}\Big[\sin 2\alpha_{b0} - m(4+5\beta_1-6\beta_2+6\beta_3\sin^2\alpha_{b0})\frac{\partial y_0}{\partial x} - 2\beta_2 h_b \sin 2\alpha_{b0}\frac{\partial^2 y_0}{\partial x^2}\Big] \tag{2a}$$

where y_0 is the shoreline change from the datum line and α_{b0} is the breaker angle at the beginning of shoreline change. Eq. (4) is the general equation of longshore sediment transport in the unsteady and nonuniform conditions. The equation of continuity for shoreline change is given by

$$\frac{\partial y_0}{\partial t} + \frac{1}{(1-\lambda)h_k}\frac{\partial Q_x}{\partial x} = 0 \tag{5}$$

where h_k is the critical depth for beach change and λ the porosity of bottom sediment. The set of equations for longshore sediment transport and continuity for shoreline change, Eq. (4) and (5), are solved for the initial and boundary conditions respectively to obtain shoreline change as diffusion or kinematic wave phenomena as discussed by Refaat and Tsuchiya[9].

(2) The equation of a stable sandy beach and its solution

The plane configuration of a sandy beach in equilibrium when longshore sediment transport along it is constant can be found by solving the set of equations for the steady and non-uniform conditions. As the second term on the left in Eq. (4) must be in the nonuniform condition when the total rate of longshore sediment transport is kept constant, the governing equations can be reduced to

$$\frac{d^2 y_0}{dx^2}+a_1\frac{dy_0}{dx}=a_0 \tag{6}$$

where

$$\left.\begin{aligned} a_1&=\frac{m(4+\cos^2\alpha_b)}{h_b\sin 2\alpha_b}\left[1-\left(\frac{h_c}{h_b}\right)^2\right] \\ a_0&=\frac{2m}{h_b}\left[1-\left(\frac{h_0}{h_b}\right)^{5/2}\right] \end{aligned}\right\} \tag{7}$$

$$\left.\begin{aligned} h_c^5&=\frac{16\alpha_2 m}{k^2\gamma^2(4+\cos^2\alpha_b)}\left(\frac{Q_x^2}{g}\right) \\ h_0^{5/2}&=\frac{16\alpha_3 C_f}{\pi k\gamma\sin 2\alpha_b}\left(\frac{Q_x}{\sqrt{g}}\right) \end{aligned}\right\} \tag{8}$$

This is a second-order ordinary differential equation for the plane configuration of a stable sandy beach for which the total rate of longshore sediment transport along it is constant. The solution can be obtained under the up and down coast boundary conditions. When the coefficients a_0 and a_1 in Eq. (7) are assumed to be constants, being the values for the initial condition, the solution is given under the boundary conditions that $y_0=0$ at the up and down coast headlands by

$$\frac{y_0}{L}=A_1\left[\left(\frac{x}{L}\right)-\frac{\exp\{-(a_1L)(x/L)\}-1}{\exp(-a_1L)-1}\right] \tag{9}$$

where

$$\left.\begin{aligned} a_1L&=\frac{m(4+\cos^2\alpha_b)}{\sin 2\alpha_b}\left(\frac{L}{h_b}\right)\left[1-\left(\frac{h_c}{h_b}\right)^5\right] \\ A_1&=\frac{a_0}{a_1}=\frac{2\sin 2\alpha_b}{(4+\cos^2\alpha_b)\left[1-\left(\frac{h_c}{h_b}\right)^5\right]}(1-\overline{Q}_x) \end{aligned}\right\} \tag{10}$$

where L is the distance between the up and down coast boundary and $\overline{Q}_x$ the ratio of the total rates of longshore sediment transport for the stable and a straight sandy beach. From this solution we conclude that when the up and down coast boundary conditions are given for a sandy beach along which the total rate of longshore sediment transport is constant, theoretically a stable beach exists, and that the plane configuration is given by the functions of a_1L and A_1.

This theoretical background for the formation of stable sandy beaches states that when two boundary conditions for shoreline change are given, a stable sandy beach can be formed between the boundaries in relation to longshore sediment transport. This is an essential principle of the methodology used for beach erosion control, in which a stable sandy beach is formed by headlands that are the boundary conditions for shoreline change.

2.3 The theoretical geometry of stable sandy beaches and its applicability

The theoretical plane configuration for a static stable sandy beach where $\overline{Q}_x=0$, is shown in **Fig. 4** in which $\alpha_B=25$ degrees, in relation to the dimensionless headland spacing a_1L. Note that a stable sandy beach exists when there is no longshore sediment transport. For an increase in the value of a_1L, the point that indicates the maximum indentation in the plane configuration is upstream in longshore sediment transport. For the expression a_1L, when the beach slope and breaker angle are constant, the maximum indentation in the plane configuration increases with an increase in the ratio of the distance between the up and down coast boundary conditions to breaker depth. **Fig. 5** shows the plane configuration when $L/h_b=150$ and $\alpha_b=25$ degrees, changing $\overline{Q}_x$. The curve for which $\overline{Q}_x=0$ in the figure is the plane configuration of a static stable sandy beach. The other curves show the configuration for a dynamic stable beach when the total rate of longshore sediment transport is constant, the plane configuration becoming flat with an increase in the total rate of longshore sediment transport when the point that indicates the maximum indentation in the plane configuration upstream in longshore sediment transport changes. The conclusion is that static and dynamic stable sandy beaches are formed naturally under the two up and down coast boundary conditions, which means that an eroding sandy beach can be stabilized when the two boundary conditions are specified effectively for controlling the shoreline change between them. This provides the theoretical background for a methodology for beach erosion control based on two effective boundary conditions.

In **Fig. 6**, for a static stable beach for which the slope is assumed to be 1/75 the indenta-

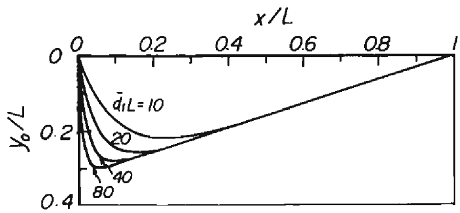


Fig. 4. Theoretical plane configuration of a stable sandy beach when the dimensionless total rate of longshore sediment transport is constant in relation to a_1/L.

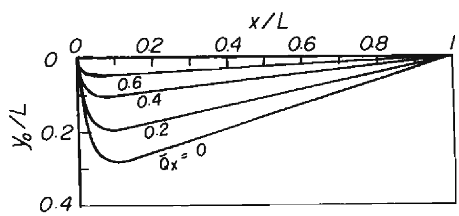


Fig. 5. Theoretical plane configuration of a stable sandy beach when $L/h_b=150$ in relation to the dimensionless total rate of longshore sediment transport, $\overline{Q}_x$

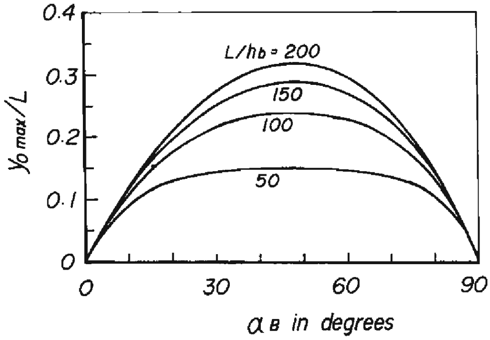


Fig. 6. The maximum indentation ratio for a static stable sandy beach in relation to the breaker angle α_b

tion ratio, $y_{0\,\max}/L$ is shown in relation to the breaker angle and the ratio of the distance between the up and down coast boundary conditions, being the headland spacing to breaker depth. This figure shows that the indentation ratio increases with an increase in the breaker angle, is maximum at the breaker angle of 45 degrees and then decreases to zero at the angle of 90 degrees. For a breaker angle range up to 45 degrees the indentation ratio agrees with Silvester's empirical relation, but beyond this there is an essential difference because the theory of a stable sandy beach configuration includes the effect of wave diffraction by headlands. In the case of normal wave incidence, however, only a straight beach is formed, evidence that the indentation ratio must be zero. Moreover, when the entire effect of wave diffraction can be introduced to shoreline change by headlands, as stated previously, a semi-circular stable sandy beach may be formed. This figure shows that when the ratio of the distance between the up- and down-coast boundary conditions to the breaker depth becomes large, the indentation ratio also becomes large, a large stable sandy beach requiring a larger indentation.

As seen in **Photo. 1** and in **Fig.** 7, in which the three curves indicate shorelines observed in 1970, 1981 and 1989, dynamic stable sandy beaches could be well formed at Amanohashidate by the first application of the sand bypassing method in Japan seven years ago. This coastline

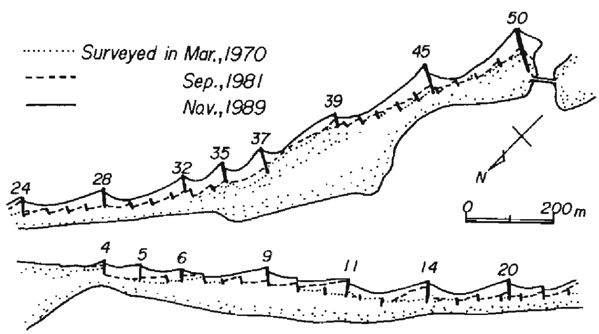


Fig. 7. A series of sandy beaches formed between groins at Amanohashidate and changes in their shorelines.

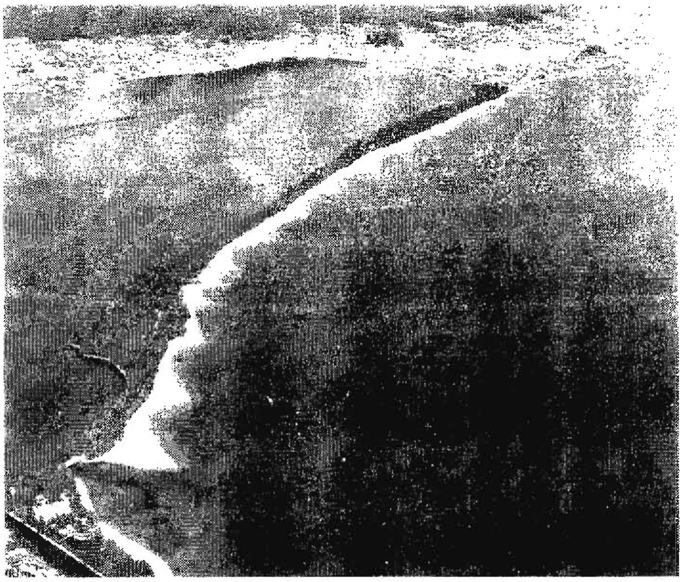
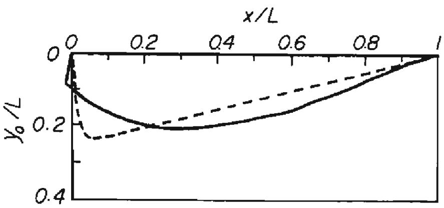


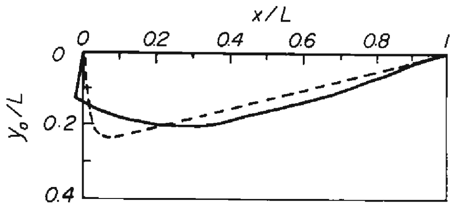
Photo. 1. Aerial photograph of the series of dynamic stable sandy beaches formed between groins by the method of sand bypassing at Amanohashidate in Miyazu Bay.

faces the bay of Miyazu for which the wave window is very narrow. The predominat wave limited by the wave window is the N48° E wave for which the height is nearly 1.0 m at a depth of 20 m, and the wave period of 8 sec was obtained by comparing the predicted and observed periods using aerial photographs. By use of wave properties, the theoretical plane configuration of sandy beaches formed between two groins is compared with the observed configuration (**Fig. 8**). In the figure the dotted curves show the theoretical plane configuration of the beach and the solid curves the observed configurations. The station numbers giving the locations of the groins correspond to the numbers in **Fig.** 7. The theoretical curves of the plane configuration of a stable sandy beach were calculated from the total rate of longshore sediment transport that was assumed to be the sand volume bypassed annually : 5,000 m^3/year. The theoretical and observed configurations agree well, except in the vicinity of the groin where the effect of wave diffraction by that structure is remarkable. However, this was not included in the theoretical configuration. **Fig. 9** shows a comparison of the theoretical and observed indentation ratios with the parameter a_1L. In the figure the dimensionless indentation ratio ($y_{0\,\max}$/ $L)A_1$ is used so that the relation is expressed by the curve alone. Some estimated values for an actual sandy beach are shown.

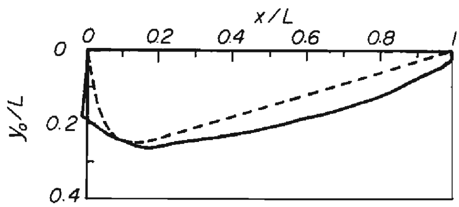
The comparison of the theoretical plane configurations of stable sandy beaches with those of actual beaches at Amanohashidate shows that dynamic stable sandy beaches exist when the total rate of longshore sediment transport is constant, and that the theoretical plane configurations agree well with observed ones, except in the vicinity of groins as no effect on wave diffraction by groins is included in the theory. Moreover, when two boundary conditions for shoreline change are given for the up and down coasts, a stable sandy beach can be formed between them by the predominant wave, so that by constructing suitable boundary conditions



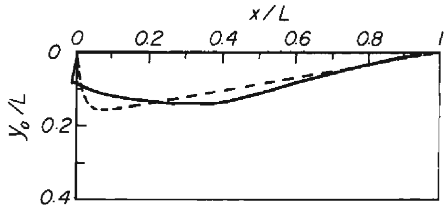
(a) Averaged configuration for the sandy beaches between headlands 11 and 15.



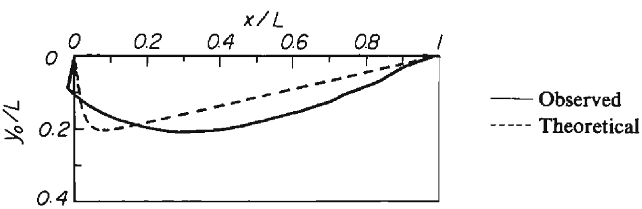
(b) Averaged configuration for the sandy beaches between headlands 15 and 20.



(c) Averaged configuration for the sandy beaches between headlands 32 and 35.



(d) Averaged configuration for the sandy beaches between headlands 37 and 39.



(e) Averaged configuration for the sandy beaches between headlands 45 and 50.

Fig. 8. Comparison of the theoretical and observed plane configurations of stable sandy beaches fromed between groins at Amanohashidate.

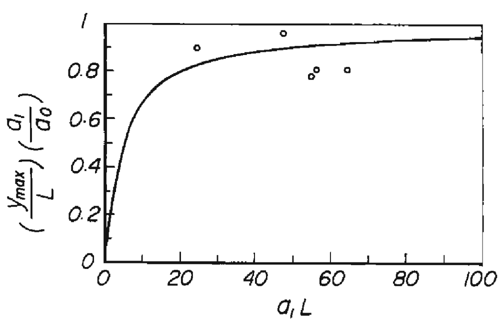


Fig. 9. Comparison of the dimensionless maximum indentation ratios of dynamic stable sandy beaches and observed ratios at Amanohashidate iq relation to a_l/L.

an eroding sandy beach can be stabilized by the method of sand bypassing.

3. Methodology for Beach Erosion Control Using Headlands and Its Applications

Since the recognition of beach erosion, various practical countermeasures for beach erosion have been taken by countries throughout the world[4]. All have aimed to prevent the erosion of sand from the beach, rather than to stabilize the beach itself. Some countermeasures in fact, are apt to accelerate erosion due to the direct influence of structures erected as countermeasures. Because of the use of such ultimately negative countermeasures, the eroding beach is not stabilized because there is no principle for stabilizing sandy beaches on which the countermeasures to be taken are based. Although such countermeasures may prevent sandy beaches from eroding for a period of several years, in the long run their existence tends to accelerate beach erosion and their collapse.

Beach erosion along a coast at the mouth of a river takes place due to lack of sediment input caused by natural change in the river's mouth, but this phenomenon is rare throughout the world (Tsuchiya, Shibano, Suyama and Yoshimura[12]). Human activities both in coastal zones and river basins are the main causes of beach erosion of sandy beaches bounded by natural headlands or formed as a delta from sediment input from a river. The phenomenon of beach erosion, therefore, can be understood only in terms of so-called large scale coastal behavior that includes the entire sandy beach and provides the basic principles for beach stabilization. As stated earlier, from natural stable sandy beaches the basic natural principles by which any sandy beach may be stabilized must be found.

From such knowledge a methodology for beach erosion control can be established. In 1976 Silvester[6] proposed the use of a headland defense for beach erosion control and introduced naturally formed static sandy beaches into the method of beach stabilization that utilizes a series of man-made headlands. He visited the Disaster Prevention Research Institute, Kyoto University in 1978 and took part in a joint investigation of beach erosion control[13]. At that time Tsuchiya, Silvester and Shibano[7] introduced his concept of headland defense (now called headland control) to Japan and extended it to the stabilization of eroding sandy beaches by the formation of a series of static or dynamic stable sandy beaches. In 1978 this procedure first was termed as the method of stable sandy beaches by Tsuchiya, Silvester and Shibano[7], but now is called methodology for beach erosion control by headlands (Tsuchiya[14, 15]). Investigations of the plane configurations of stable sandy beaches formed experimentally by offshore breakwaters have been extensively carried out by Hsu, Silvester and Xia[16] and Silvester and Hsu[17] to clearly specify the plane configuration of a static stable sandy beach. However, as no theoretical background on the formation of the natural stable sandy beaches existed, a theory of the formation of stable sandy beach has been formulated. Here the basic principle for beach erosion control is discussed and on the basis of the formation of stable sandy beaches a methodology for beach erosion control is proposed for two types of sandy beaches, those bounded by two headlands and those formed as river deltas.

3.1 Methodology for beach erosion control

In the stabilization of an eroding sandy beach, the basic roles of man and nature are to be considered. Brunn[18] stated that "Nature's engineering does not always satisfy man's ambitions. Man, however, learned from nature. Combining nature and man's efforts practical solutions have been obtained." And Silvester[13] proposed as a methodology for beach erosion control, "How to copy nature." Such statements may reflect the idea of Vierlingh (Brunn[18]) that "Water shall not be compelled by any fortse, sic, [force], or it will return that fortse onto you." I believe that to preserve our coastal zones from beach erosion, these principles must be kept in mind and that never should technical skills and achievement be used over–confidently in the countermeasures taken for controling beach erosion. In practice, one has to learn the basic principles from nature and use them to establish a methodology for controlling beach erosion that also effectively stabilizes eroding sandy beaches.

(1) Conservation of the sedimentation system

Two types of sedimentation systems operate on natural sandy beaches. The first is due to changing beach profiles caused by wave conditions as has been shown clearly by Wright and Short[19] and Sunamura[20]. Wright and Short classified beach profiles into three types: dissipative, intermediate and reflective beaches, each of which has different characteristic processes. The intermediate type is the result of the three–dimensional behavior of a sandy beach, which Inman and Frutschy[21] termed a sedimentation cell. They demonstrated that many sedimentation cells exist on natural coastlines and together constitute a sedimentation system. Such a system encompasses the entire beach process, for example, sand beaches that are generally bounded by two neighboring headlands or are formed as river deltas. These beach processes are investigated as so–called large scale coastal behavior governed by the sedimentation system. In such a system the essential principle is the conservation of sediment, the continuity of sedimentation constituting a natural circulation system of sedimentation.

For natural sandy beaches, a sedimentation system is formed during long–term change. Due to human development of river basins and coastal zones, as well as the erection of coastal structures as beach erosion countermeasures, sedimentation systems have had to change, and some have been destroyed. A sedimentation system will recover unless destroyed; once destroyed there is no chance of recovery. Therefore for sandy beach preservation, the sediment conservation in the system must be based on natural, essential principles.

(2) Laws for wave energy dissipation and sediment transport

Highly efficient wave energy dissipation is required to preserve sandy beaches. This results in the effective reduction of wave reflection by the beaches and the existence of offshore sediment transport. Moreover, it maintains the continuity of longshore sediment transport. The wave run–up on a sandy beach can be used to evaluate the efficiency of wave energy dissipation. **Fig. 10** shows the dimensionless expression of wave run–up on a slope obtained from Saville's experimental data[22]. In the figure, R/H_0 is the dimensionless wave run–up height relative to the wave height in deep water, H_0/L_0 the wave steepness, h/H_0 the ratio of the water depth to wave height in deep water, and β the beach slope. This figure demonstrates that the wave run–up height becomes very high on a sandy beach steeper than 1/3, but decreases rapidly on a beach less than 1/10 and that this tendency is independent of the wave period. These wave run–up characteristics show that sandy beaches that are highly efficient for

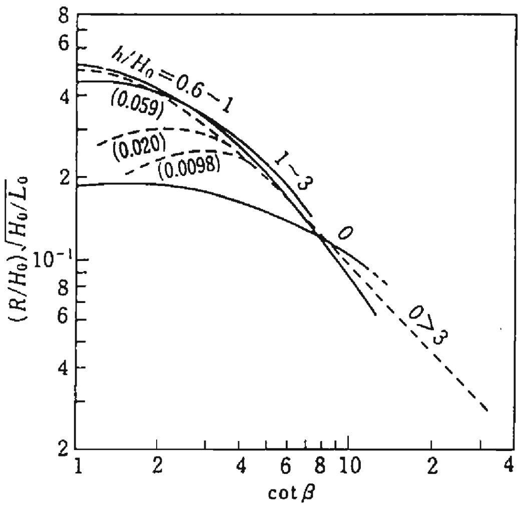


Fig. 10. Characteristics of wave run–up on a gentle slope in dimensionless form for $\tan\beta=m$.

dissipating wave energy are those with slopes less than 1/10. The conclusion is that the beach most effective for wave energy dissipation is a sandy one with a gentle slope.

As explained previously, the total rate of longshore sediment transport along a sandy beach must be constant to maintain its stability. The total rate of longshore sediment transport, therefore, has an important function in the stabilization of a sandy beach against erosion. Eq. (3) shows that the total rate of longshore sediment transport is proportional to the 5/2 power of the breaker depth, $(h_b)^{5/2}$ where h_b is the breaker depth and to $\sin 2\alpha_b$ where α_b is the breaker angle. As the water depth decreases, the total rate of longshore sediment transport decreases rapidly, so that a change in the water depth may result in shoreline change. When the breaker angle increases, the total rate of longshore sediment transport also increases. However, as Brunn[19] reported, the total rate of longshore sediment transport is changed so effectively by changing the breaker angle that it may result in rapid shoreline change. Therefore, from the principle of the streamline based on the idea of Vierlingh, locations of rapid change and discontinuity in longshore sediment transport must be avoided in sandy beach preservation.

(3) Beach erosion control by regulation of the total rate of longshore sediment transport

To stop beach erosion what must be controlled? Generally, beach profiles should be gentle in relation to the characteristics of beach sediment, and we must learn from natural sandy beaches what very high wave energy dissipation efficiencies must be formed so that there is no offshore sediment transport by reflected waves. For this purpose no structure should be erected unless absolutely necessary. If a measure to prevent sand run–off is needed, a sandy beach profile should be formed by a structure, that enhances the efficiency of wave energy dissipation by the sandy beach formed for beach stabilization.

Sepecifically, what must be done for effective beach erosion control when stabilizing sandy beaches? Along coastlines near river mouths, for example, beach erosion is severe if the sediment input from the river decreases. The coastal shoreline having retreated, little change in the total rate of longshore sediment transport occurs because there is no change in the wave conditions and this results in severe beach erosion. If the sediment input from the river decreases, the total rate of longshore sediment transport therefore must be regulated. As the total rate of longshore sediment transport is expressed by Eq. (3), there are two methods for effective control: 1) reduction of breaker depth and 2) reduction of breaker angle, thereby reducing the total rate of longshore sediment transport so that it approximates the designed total rate needed along the beach. These methods are explained briefly hereafter.

(a) *Control of breaker depth* To change breaker depth along a sandy beach the bottom topography has to be changed artificially. Taking into account the predominant wave, a wide man–made shoal or reef and broad–crested submerged breakwaters must be used so that breaker height is reduced by wave reflection of the shoal, by the reef, or a combination of both. Wave reflection can be used to control breaker depth within a narrow range of wave frequencies, thereby obtaining the designed total rate of longshore sediment transport. Care must be taken because with some measures the breaker angle may be changed because of change in the breaker depth, the result being that there is no control of the total rate of longshore sediment transport. Although control of breaker depth is the principal application for the control of breaker height, bottom topography change also must be predictable and maintained so that breaker height is controlled. When broad–crested submerged breakwaters are used, wave reflection may become an important factor in the control of breaker height, but if the wave angles are changed, the total rate of longshore sediment transport also will change. Changes in wave height distribution result in changes in radiation stress that may produce changes in nearshore currents, in turn causing offshore sediment transport over the submerged breakwaters.

(b) *Change in breaker angle* Sandy beaches are formed naturally when the breaker height along the beach is steady. By changing only the breaker angle along the beach the total rate of longshore sediment transport can be controlled to give the designed total rate. In practice, when the methodology for beach erosion control by headlands is applied, a series of sandy beaches are formed, making the orientation of the shoreline between headlands somewhat oblique so that the total rate of longshore sediment transport is reduced. When headlands are separated by considerably long distances, sandy beaches may form naturally between them.

(4) Methodology for beach erosion control by headlands

Two typical, ideal examples can be used to explain the proposed methodology for beach erosion control by headlands. The first is beach erosion near a river mouth caused by a decrease in the sediment input from the river. The second is beach erosion caused by a large coastal structure.

(a) *Beach erosion control in a river delta* Due to a lack of, or decrease in, sediment inputs from rivers, severe beach erosion has taken place throughout the world, especially in the Nile River delta in Egypt and in Japan, especially along the Niigata, Kochi, and Tenryu coasts. Beach erosion along a river mouth delta can be considered a reduction process of the delta due to a decrease in sediment input from the river. To understand this type of beach erosion the reduction process of the river delta must first be considered theoretically in order to determine what happens during reduction in relation to delta formation. Bakker and Edelman[23] proposed a theory for the evolution of a river delta, and Komar[24] calculated

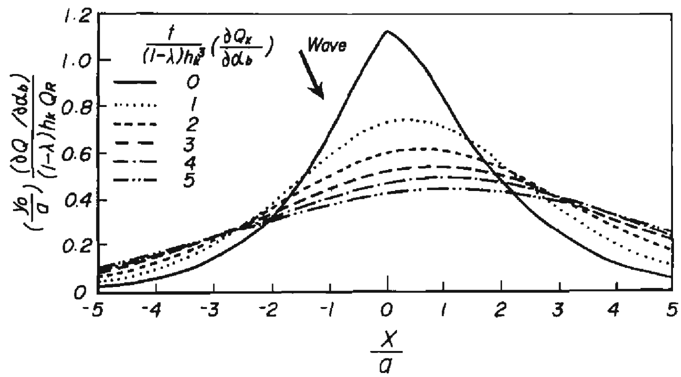


Fig. 11. Theoretical reduction process of a river delta due to lack of sediment input from the river in the case of oblique wave incidence.

shoreline evolution numerically. Recently Refaat and Tsuchiya[9] proposed a theory that accounts for the formation and reduction processes of a river delta for both normal and oblique wave incidences. **Fig. 11** gives an example of the theoretical prediction of shoreline retreat as part of the reduction process of a river delta, indicating the respective reductions of a river delta by obliquely incident wave. It is clear that due to a decrease in or lack of sediment input from the river, severe shoreline retreat takes place near the central part of the river delta. The eroded sediment is deposited both on the up and down coasts, resulting in shoreline accretion in the normal incident case. Accretion takes place both on the up and down coasts when there are oblique incident waves, but more sediment is deposited along the down coast due to sediment transport in the longshore direction. When contemplating measures for the preservation of sandy beaches along a river delta coastline, such phenomena must be kept in mind. If the countermeasures for beach erosion utilize structures, most of the eroded sediment may be transported in the offshore direction due to wave reflection by these structures, only a little sediment being transported downcoast. Such erosional and depositional phenomena can be clearly seen in the reduction process of the Nile River delta (Fanos, Khafagy and Komar[25]). Therefore, by the use of a long-term shoreline prediction model large scale coastal behavior can be understood by considering such beach erosion processes a reduction process of the river delta. A series of sandy beaches is formed by constructing headlands to reduce longshore sediment transport in the eroding central area of river delta and by creating sandy beaches down coast and extending them to the depositional area. The total rate of longshore sediment transport along the sandy beaches is gradually reduced by shortening the lengths of the headlands in the direction of longshore sediment transport.

As beach erosion can be considered a reduction process of a river delta caused by a decrease in sediment input, the beaches must be stabilized. Suppose that for the delta of a river flowing into the sea, the predominant wave is incident on its sandy beach from the direction of the incident angle θ_B, resulting in the total rate of longshore sediment transport Q_x. Assume that the sediment input, as the sediment source from the river, was Q_R, but has recently decreased to Q'_R. Beach erosion has taken place along the coastline to the left of the river, seen as shoreline retreat in **Fig. 12.** The total rate of longshore sediment transport by the pre-

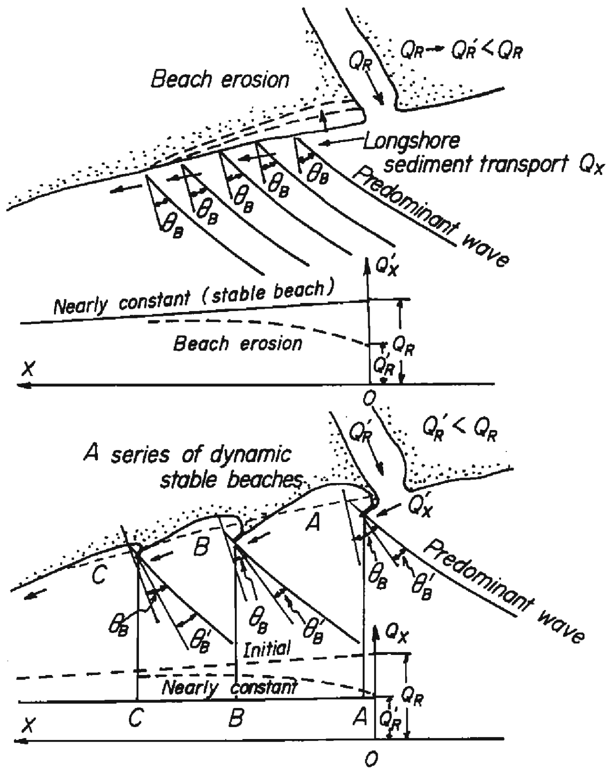


Fig. 12. Ideal methodology for beach erosion control along the coast of a river delta where sediment input from the river has been reduced.

dominant wave is assumed to be nearly constant alongshore so that because of the decrease in sediment input, beach erosion has begun near the river mouth and is propagating in the downstream direction.

As shown in the figure, to stabilize this sandy beach against beach erosion, a series of dynamic stable sandy beaches have to be formed under the given condition of reduced sediment input from the river. At the end of river mouth deltas there usually is a spit at which the total rate of longshore sediment transport is constant or a headland at which no shoreline change can be assumed. Therefore, a series of headlands constructed along the beach will gradually reduce the total rate of longshore sediment transport so that it becomes constant at the downstream end (the derivative of the total rate becomes zero there), meaning that there is no shoreline change at the headland.

(b) *Control of beach erosion by large coastal structures* The construction of a harbor on a sandy beach where there is longshore sediment transport causes beach erosion. When the harbor is constructed near a river mouth, beach erosion is particularly severe because structures interrupt longshore sediment transport down coast. This type of erosion can be called structure–induced beach erosion, the main causes being the interruption of longshore sediment transport and change in the nearshore currents due to wave diffraction by the structures.

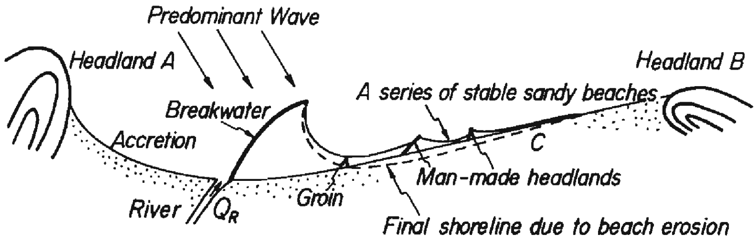


Fig. 13. Ideal methodology for control of beach erosion caused by a large coastal structure constructed on a sandy beach bounded by two headlands.

More detailed examination shows that due to this type of beach erosion, the large scale nature of the entire sandy beach undergoes essential and wide-ranging changes. In this case the most effective countermeasure for controlling the erosion is the use of sand bypassing from the river mouth to the down coast area to satisfy the continuity condition of sediment transport alongshore. But, when the structure is very big, another cause of beach erosion will operate (Tsuchiya, Yamashita and Silvester[26]). As shown in **Fig. 13**, if the structure is large enough to act as a headland, a new sandy beach with the boundary condition for shoreline change by the headland will be formed, meaning that the down coast area is eroded continuously. Sea dikes or offshore breakwaters have been used locally to prevent beach erosion, but this type of beach erosion can not be so controlled. A new sandy beach or new bottom topography is formed under the structure-given conditions, usually producing a steep beach profile. Thus beach erosion tends to accelerate markedly due to the direct influence of man-made structures. As longshore sediment transport occurs along the beach, erosion in the down coast direction is continuous.

Thus for the formation of a new sandy beach to stabilize the existing sandy beach against erosion, either static or dynamic stable beaches must be formed by the construction of a series of headlands down coast. A schematic arrangement of such headlands is shown in **Fig. 13**, the dotted curve indicating the new sandy beach to be formed by the breakwater on the straight beach and the curved beaches formed by headland construction down coast. When a large coastal structure such as a breakwater is constructed, it must be a headland that effectively controls the formation of a new sandy beach, but structure-reduced beach erosion is severe and continuous in the down-coast direction, resulting in change in large scale coastal behavior itself. To stabilize a sandy beach that is being eroded, as previously concluded, theoretically two headlands are needed as boundary conditions for shoreline change. When a headland is constructed, however, wave diffraction results in local change in the bottom topography even though the structure may not itself affect shoreline change. To compensate for the effect of the headland on shoreline change another headland is needed for the gradual reduction of the effect of the first.

Headlands are constructed offshore or inside the breaker zone. The position of a headland is determined by the factors necessary to protect the beach, in particular headland spacing and the width of the sandy beach. When the offshore toe of the headland is beyond the surf zone, a well-formed static stable sandy beach is produced for which there is no longshore sediment transport even under the condition of obliquely incident waves. When headlands are constructed in the surf zone, dynamic sandy beaches are formed by means of sand bypassing from the end down coast to the end up coast.

Sandy beaches usually are bounded by headlands or other types of boundaries, and harbors often are constructed on these beaches. To control beach erosion along the entire beach it is first necessary to investigate and to understand large scale coastal behavior; e. g. by establishing a long–term shoreline change prediction model by which to hindcast shoreline change or the long–term process of the formation of a sandy beach. By the use of this prediction model, the most suitable locations for the placement of the artificial boundary conditions that determine shoreline change can be found. A series of headlands that constitute the boundary conditions for shoreline change can then be spaced suitably so as to produce a series of well–stabilized sandy beaches.

(c) *Application of the methodology for beach erosion control by headlands with sand bypassing* In nature, due to the position of headlands extending offshore or inside the surf zone, stable sandy beaches are formed that are in static or dynamic equilibrium conditions. When headlands extend far enough beyond the surf zones to completely disrupt longshore sediment transport, a static stable sandy beach may be formed between them. When headlands are constructed within the surf zone, longshore sediment transport will continue beyond the headlands so that a dynamic stable sandy beach may be formed. In the case of headlands extending offshore so that there is no sediment movement, a static stable sandy beach can be formed if the headlands satisfy the boundary conditions necessary for shoreline change. Beach nourishment is required in the formation of such a sandy beach; no sand bypassing is needed. In the latter case, however, when headlands are constructed within the surf zone, sand bypassing is required for the formation of a stable sandy beach. If, however, no sand bypassing takes place, a sandy beach formed by beach nourishment may retreat gradually due to high waves. In the case of a dynamic stable sandy beach, sand bypassing maintains the beach, but the total bypass rate depends on the water depth of the offshore toe of the headland.

(d) *Headlands as boundary conditions for shoreline change* As previously discussed, to stabilize an eroding sandy beach, theoretically two boundary conditions are needed up and down coasts for longshore sediment transport. The boundary condition is a means of mathematically controlling shoreline change effectively. When a headland such as Silvester[27] suggested for headland control is constructed, it will have a structure–induced effect on shoreline change locally and sometimes more widely. If the effect becomes marked because of wave reflection and diffraction by the headland, no well–formed stable sandy beach will be established between headlands. Therefore, methods must be established by which to construct a headland that satisfies the mathematical boundary condition for shoreline change. From our experience in constructing groins and offshore breakwaters, a suitable headland can be constructed. However, as the structure itself affects shoreline change, more effective structures that satisfy boundary conditions must be devised. Silvester[27] investigated various shapes and orientations of headlands, but further structural considerations must be taken into account in order to reduce structure–induced effects on shoreline change.

Naturally formed headlands have an effective bottom topography that reduces local wave reflection. The topographies of natural headlands and small islands should be applied to the design of effective headlands. The problems encountered with constructed headlands can be solved by the practical applications of headland control. Improvement then can be made in constructing headlands that have low wave reflection.

3.2 Formation of stable sandy beaches

Some applications of the methodology of beach erosion control by the use of headlands are described : 1) The case of static stable sandy beaches constructed for the preservation of a pocket beach, Shirarahama in Wakayama Prefecture (completed satisfactorily) ; 2) Use of static or dynamic stable sandy beaches along the Joetsu–Ogata coast facing the Japan Sea and the Kuta and Nusa Dua beaches in Bali (the Japanese beach now under construction and the Indonesian beaches having been partly completed) ; 3) Dynamic stable sandy beaches combined with a method of sand bypassing on Amanohashidate, a sand spit in Miyazu Bay (completed) and on the Kaike coast facing the Japan Sea (proposed). The practical methodology and its applications are explained briefly ; for details see the original references.

(1) The static stable sandy beach used to preserve Shirarahama, a pocket beach [28]

As seen in **Fig. 14(a)**, Shirarahama, a natural pocket beach, is bounded by two natural headlands, Gongenzaki and Yuzaki. Due to the gradual decrease in sediment input from the small Teratani River because of urbanization of the hinterland there has been gradual beach erosion. To obtain a wider sandy beach, a static stable sandy beach was formed by extending the Gongenzaki headland about 30 m offshore by the use of giant stones and by constructing a headland of the T–shaped groin type at another position. To reduce wave reflection, the groin was given a mild slope of 1/5 on its offshore face and was constructed of giant stones. Extensive physical and numerical experiments on waves, currents and beach changes were done to determine the compatibility conditions necessary for the good formation of a stable sandy beach between the two headlands. The final result, **Fig. 14(a)** shows how, by use of the most suitable type of beach nourishment a stable sandy beach can be well formed. The condition is explained schematically in **Fig. 14(b)** in which two sandy beaches, A and B, are formed by a set of two headlands, that correlate well and form a static stable sandy beach about 600 m

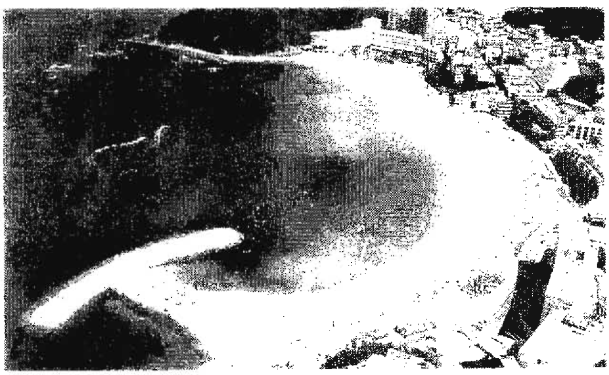
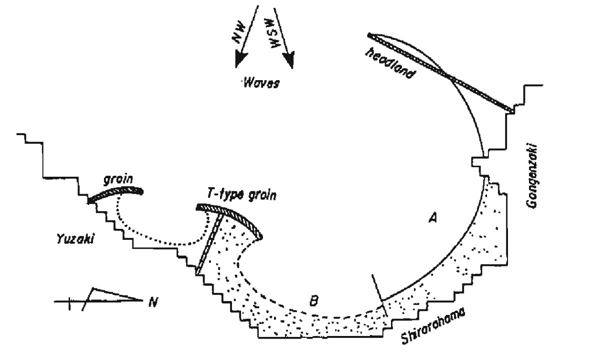
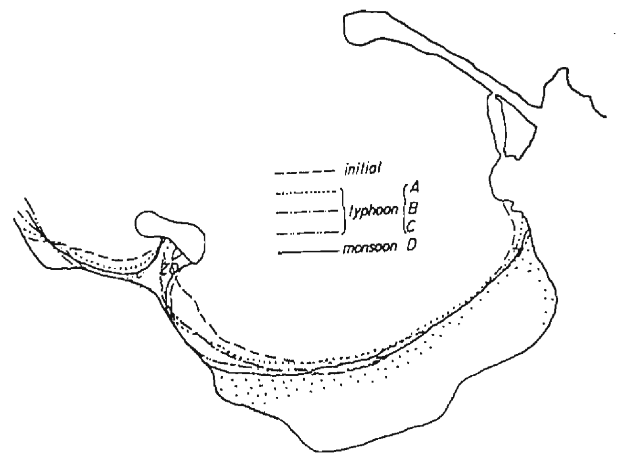


Photo. 2. Aerial photograph of the static stable sandy beach formed between Gongenzaki headland (right) and the T–shaped headland at Shirarahama.



(a) Location of Shirarahama and the compatibility condition.



(b) Experimental verification of the formation of a stable sandy beach.

Fig. 14. Compatibility condition for the formation of a static stable sandy beach by two headlands at Shirarahana.

long. Construction of the headlands and beach nourishment were completed in 1992 (**Photo. 2**).

(2) Static and dynamic stable sandy beaches applied to the Joetsu–Ogata coast and Kuta and Nusa Dua beaches in Bali

Severe beach erosion may take place due to the lack of longshore sediment transport caused by large coastal structures such as breakwaters or natural tombolo formations produced by an island. In the first case, when a harbor is constructed on a sandy beach bounded by two headlands, severe beach erosion usually takes place because of the lack of longshore sediment transport and the change in large scale coastal behavior. A typical example is given to explain how to stabilize such a beach by forming a series of stable sandy beaches. The second case is a rare one in which longshore sediment transport has gradually been interrupted due to the formation of tombolo by a small island in Bali.

(a) *Application to the Joetsu–Ogata coast*[29] The Joetsu–Ogata coast faces the Japan Sea and extends about 25 km between the Gotsu and Yoneyamazaki headlands. The Seki and Kakizaki Rivers that flow to the coast are the sediment sources. The main causes for beach erosion are considered to be : 1) Interruption of longshore sediment transport by the west breakwater of Naoetsu Harbor. 2) Change in nearshore circulation due to change in the wave field produced by the breakwater. 3) Wave reflection by sea dikes and offshore breakwaters that were constructed as beach erosion countermeasures, resulting in offshore sediment transport because of change in the beach profile. Although these countermeasures were constructed, beach erosion and collapse have been frequent with the result that there has been no formation of sandy beaches in front of the structures.

To understand the beach formation process, large scale coastal behavior can be studied by constructing a long–term shoreline prediction model based on the so–called one–line theory of shoreline change. By introducing the predominant monsoon wave into the long–term shoreline change prediction model, hindcasting of shoreline change before severe beach erosion had begun could be made and compared with the 1961 shoreline for three cases under the conditions of 1) no sediment input from the sediment sources of the Seki and Kakizaki Rivers, 2) sediment input given as 10,000 m^3/yr and 5,000 m^3/yr respectively from these rivers, and 3) sediment input given as 100,000 m^3/yr and 5,000 m^3/yr from the same rivers. The hindcasted values agreed well with the 1961 shoreline, but there is no marked influence of sediment input on long–term shoreline change. We consider that the shoreline change model explains the formation process of the coast including such conditions as headlands, locating the most suitable placement of headlands so that a series of stable sandy beaches are formed. Long–term shoreline change prediction gives the longshore distribution of the total rate of longshore sediment transport as shown by the solid curve in **Fig. 15**. In this figure the current distribution of the total rate of longshore sediment transport, estimated from the bottom topography change, is shown by the dotted line. Comparison of the curves estimated for long–term shoreline and bottom topography changes shows that the direct effect of the construction of Naoetsu Harbor on longshore sediment transport has already reached the Ogata fishing harbor, and in the vicinity of Naoetsu harbor the direction of longshore sediment transport has

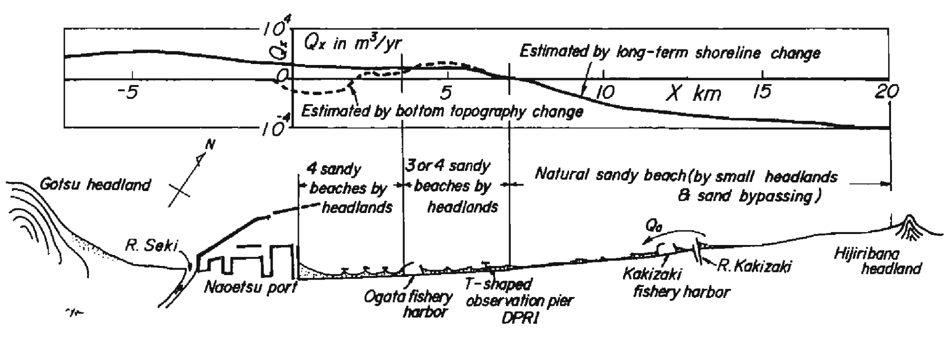


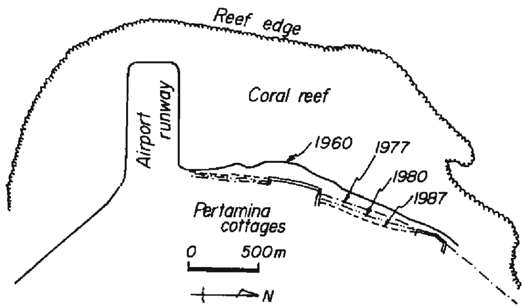
Fig. 15. Longshore distributions of the theoretical and estimated total rates of longshore sediment transport and the methodology proposed for stabilizing the Joetsu–Ogata coast.

changed to the westerly direction. The prediction of long-term shoreline change shows that if a headland were placed near the Shinbori River, just west of the Ogata fishing harbor, the shoreline would reach equilibrium, resulting in a stable sandy beach even when the effect of wave diffraction by the headland is included. If a headland is constructed at the correct position, a stable sandy beach will be formed between the headland and the harbor; but, the effect of that headland might be such that another headland might be needed to reduce it. A series of headlands therefore has been proposed (see **Fig. 15**) to stabilize the coast against severe beach erosion. In the area near the Kakizaki River, the sandy beach has been stable. However, due to the construction of small jetties at the river's mouth and the Kakizaki fishing harbor, the system of longshore sediment transport has broken down. To restore the system, a series of small headlands could be constructed to stabilize the beach combined with sand bypassing to the west.

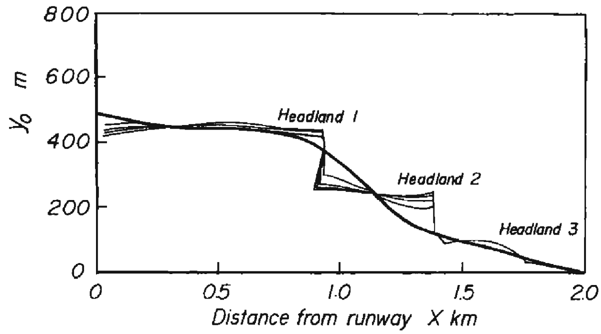
Two ways to form a series of stable sandy beaches are by the construction of static and dynamic stable beaches. In the case of static stable sandy beaches, the headlands should extend offshore beyond the surf zone to stop longshore sediment transport completely. Sand bypassing therefore is not essential after construction of the headlands and beach nourishment. In the case of dynamic stable sandy beaches, however, headlands with mild slopes can be constructed inside the surf zones, but sand bypassing is essential because longshore sediment transport occurs at the headland toes. Some longshore sediment transport, however, would still occur after headland construction. A series of static stable sandy beaches, therefore, has been proposed. Two headlands at locations very near to Naoetsu Harbor are under construction. It is my belief that a well-formed stable sandy beach will be produced by these headlands thereby verifying the use of this methodology for the long-term stabilization of this coastline.

(b) *Application to Kuta and Nusa Dua beaches in Bali*[30),31)] The Kuta and Nusa Dua beaches in Bali respectively face the Bali Strait and the Indian Ocean. The Kuta beach has undergone erosion since an airport runway was constructed on a coral reef there in 1968, which altered wave and nearshore currents along the reef, resulting in changes in the sedimentation cell. The Nusa Dua beach has undergone erosion since formation of tombolos behind Nusa Kucir and Besar islands several decades ago, resulting in the interruption of longshore sediment transport so that today transport no longer exists in the northern direction.

To prevent severe beach erosion, the headland methodology for its control was applied using a series of static stable sandy beaches. In brief, for the Kuta beach, long-term shoreline change first was hindcast using the long-term shoreline prediction model (Yamashita, Tsuchiya, Matsuyama and Suzuki[32)]) in which the most effective wave for shoreline change on coral reefs was used to investigate large scale coastal behavior and to check the applicability of the model. The most effective headland positions were found from the numerical prediction of shoreline change by headlands. Results are shown in **Fig. 16(a)** and **(b)**, **(a)** showing the location of the beach and the three proposed headlands and **(b)** indicating the shoreline change produced by the headlands. In this figure the unbroken curves indicate continuous shoreline change for an interval of 30 hrs. They demonstrate that shoreline change tends to approach stability even if the influence of wave diffraction by the headlands is excluded from the prediction and that if a headland arrangement is used three headlands appear to be sufficient to stabilize the beach. Two of the three headlands were constructed by a groin and offshore



(a) Location of Kuta beach and the arrangement of three headlands.



(b) Predicted long-term shoreline change.

Fig. 16. Predicted long-term shoreline change used to establish the most effective arrangement of headlands at Kuta beach in Bali.

breakwater respectively. After their construction a sandy beach formed naturally between the headlands. **Photo. 3** shows this sandy beach in 1989, with swell breaking simultaneously along it. To reduce the local influence of man-made structures, further improvement is needed in the design of effective headlands of the groin and offshore breakwater type. The sandy beach along which many tetrapods have been placed, approaches the form of the static stable beach in **Fig. 17** in which the solid and dotted curves respectively indicate measured and predicted shorelines based on the empirical relation found by Hsu, Silvester and Xia [16] for a static stable beach. Clearly a static stable coral-sand beach has been well formed between the headlands by the use of the proposed methodology for beach erosion control, and the formation of such a beach is effective for beach stabilization. When I revisited Bali in 1990, however, the coral-sand beach that had been forming so wonderfully was no longer there. Dr. Syamsudin and I were disappointed by the reconstruction of this beach with two big groins to make a marine resort, rather than beach preservation.

Another application of beach preservation made at Nusa Dua beach used a series of static stable sandy beaches combined with a method of sand bypassing that extended from the southern coast near Nusa Besar Island to the northern end of the beach, the total amount of which

Photo. 3. View of the sandy beach formed between the headlands at Kuta beach in Bali. Photo taken in 1989 looking north from a groin type headland.

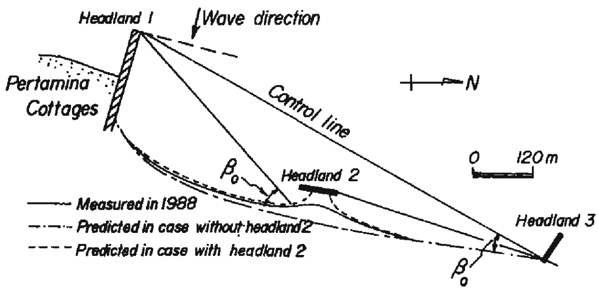


Fig. 17. Shoreline change after the construction of two headlands, and the shoreline predicted by the empirical relation for a stable beach at Kuta beach in Bali.

may be nearly the total rate of longshore sediment transport. An L–shaped headland of the mild–slope groin type was constructed of stones placed on the coral reef. Beach nourishment amounting to 40,000 m^3 was made between the headland and Nusa Kecir Island in 1987. One of the sandy beaches formed between the headland and Nusa Kecir Island is shown in **Photo. 4** and **Fig. 18(a)** and **(b)**. The shorelines along two small islands are shown in (a) together with those predicted by the empirical relation for a static stable sandy beach (Hsu, Silvester and Xia [16]). Shoreline change after construction is shown in (b). **Photo. 4** shows the beach in the southern direction. From the figure and photograph it is clear that this wonderful well–formed beach is a static stable sandy beach.

(3) Dynamic stable sandy beaches have been used at Amanohashida and have been proposed for the Kaike coast

(a) *Application to Amanohashidate, a sand spit*[33] The sand spit called Amanohashidate in Miyazu Bay that faces the Japan Sea has suffered severe beach erosion due to construction of a fishing harbor up the coast. Amanohashidate is a well–formed sand spit created by obliquely incident waves that pass through a very narrow wave window. As the headlands have been constructed in very shallow water (**Photo. 1**), longshore sediment transport exists beyond the headlands when there are high waves. As previously described, a series of dynamic stable sandy beaches therefore have been formed between the headlands ; but due to wave transformation and concentration, shoreline fluctuations have occurred resulting in variation in the

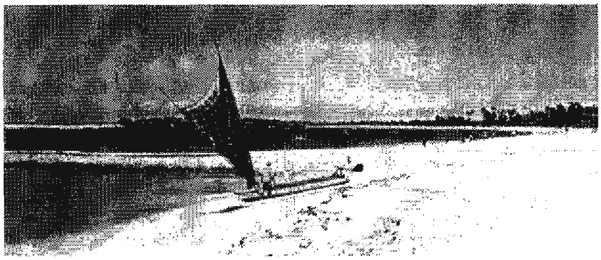
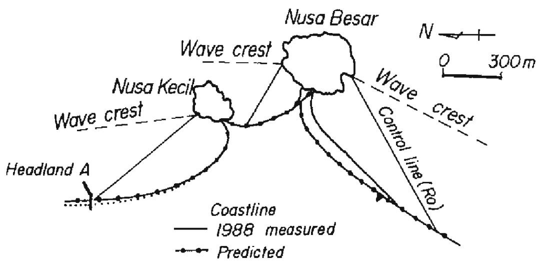
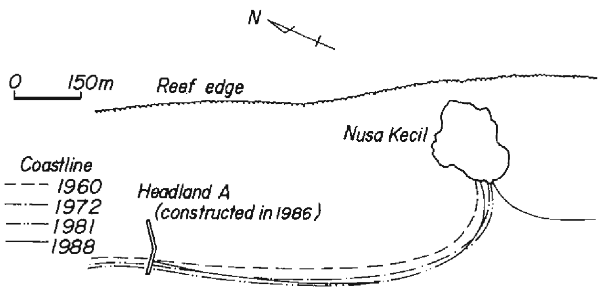


Photo. 4. View of the sandy beach formed between Nusa Kecir Island and the headland at Nusa Dua beach in Bali. Photo taken in 1992 looking south from the headland.



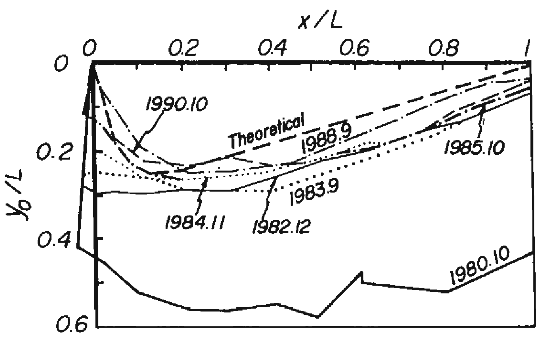
(a) Shoreline changes along two islands, the headland, and the change predicted by the empirical relation for a static stable beach.



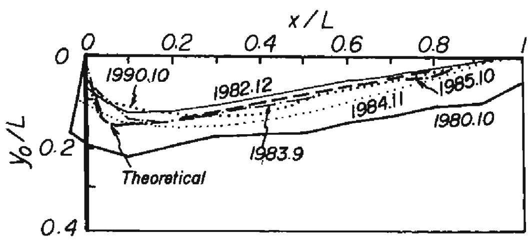
(b) Shoreline change after headland construction

Fig. 18. Shoreline change after headland construction, and the shoreline predicted by the empirical relation for a static stable beach at Nusa Dua beach in Bali.

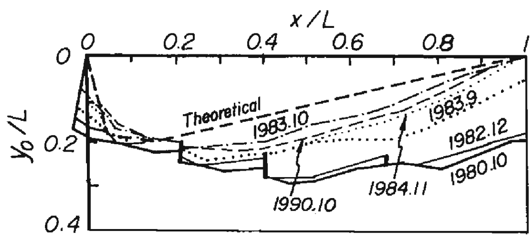
total rate of longshore sediment transport along the beach. Shoreline configurations several years after construction of the headlands and sand bypassing are compared with the theoretical configurations in **Fig. 19**, in which the dotted curve indicates the theoretical shoreline of a dynamic stable sandy beach and the other curves the actual shorelines measured in the year shown. The shoreline configuration gradually approaches the theoretical except in the vicinity of the headlands. **Fig. 20** shows the annual change in the shoreline inclination of the sandy



(a) Between headlands 32 to 35.



(b) Between headlands 37 to 39.



(c) Between headlands 45 to 50.

Fig. 19. Changes in the plane configurations of the sandy beaches formed between groins at Amanohashidate in comparison with the theoretical plane configurations of dynamic stable sandy beaches.

beaches formed between the groins positioned at intervals. The inclination clearly tends to approach the constant. When the observed value has nealy reached the theoretical one, fluctuation in the total rate of longshore sediment transport has decreased and the volume of deposited sediment on the sandy beaches has increased slightly, approaching the constant. Therefore, the sandy beaches formed between the groins are concluded to have already been in dynamic equilibrium; they have been dynamic stable beaches. The total rate of longshore sediment transport, the annual sand bypass volume, was estimated to be about 5,000 m^3/yr.

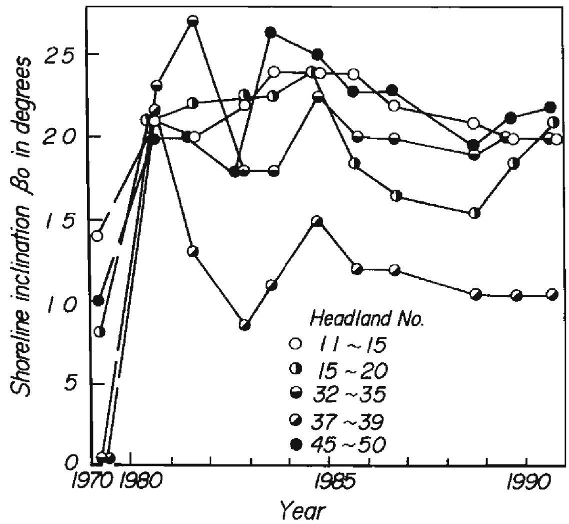


Fig. 20. Annual change in the shoreline inclinations of the sandy beaches formed between groins at Amanohashidate.

Further investigations may be required to establish a methodology for beach erosion by headlands that takes into account the general relationship between the geographic situation of the sand spit, the predominant incident waves, and their breaking lines along the sandy beaches.

(b) *Application to the Kaike coast facing the Japan Sea* As reported (Silvester, Tsuchiya and Shibano[8)]) the Kaike coast (**Fig. 21**) has undergone erosion due to a decrease in sediment input from the Hino River. Many countermeasures have been instituted, most recently, the construction of a series of offshore breakwaters. Tombolos are formed between these offshore breakwaters, but the bottom topography off these breakwaters gradually has been deepening

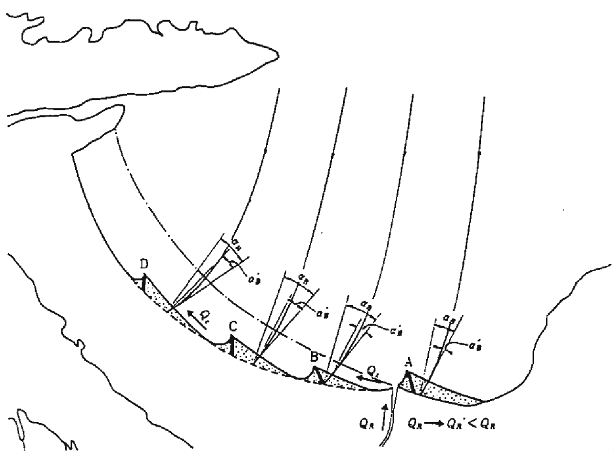


Fig. 21. The Kaike coast facing the Japan Sea and the ideal methodology for sandy beach stabilization by the creation of a series of dynamic stable sandy beaches.

due to wave reflection. Before construction of the offshore breakwaters, offshore sand bars existed alongshore the sandy beach (Toyoshima[34]). These have disappeared due to the marked change in the beach profile. The marked change in the bottom topography near the offshore breakwaters has resulted in a greater water depth, leaving no possibility for stabilizing the sandy beach by the formation of stable sandy beaches.

This is the ideal place to use the methodology for beach erosion control by headlands. This is a barrier coast formed by longshore sediment transport from the sediment source, the Hino River. However, the present condition of beach erosion is the same as at Amanohashidate, a typical sand spit. As shown schematically in **Fig. 6**, the fundamental methodology for beach stabilization is to form a series of dynamic stable sandy beaches by sand bypassing. Once the barrier beach formation process could be shown as large scale coastal behavior using a long-term shoreline prediction model (Tsuchiya, Yamashita, Izumi and Tottori[29]), the most suitable arrangement of headlands, which would stabilize the beach by the formation of a series of dynamic stable sandy beaches between them could be determined. In this arrangement, the total rate of longshore sediment transport along the beaches could be reduced by the sequence of headlands that would start at the river's mouth, becoming zero at the end headland. Another proposal, also made by Silvester, would create a series of static stable sandy beaches whose shorelines must be normal to the predominant wave in order to stop longshore sediment transport completely, even through a little sediment input can be expected from the Hino River.

3.3 Formation of stable sandy beaches in the reduction process of a river delta

Along the Niigata coast severe beach erosion has occurred since breakwaters were constructed on the west side of the mouth of the Shinano River, and it has been accelerated by the short-cutting of the river and by ground subsidence. No consideration of beach erosion has been made as part of the reduction process of the river delta. Countermeasures erected against beach erosion have been groins, sea dikes, offshore breakwaters and mild-slope revetments used successively to prevent shoreline erosion. These countermeasures have been effective against severe beach erosion, but little sandy beach is preserved when change makes the beach profile steep. From this experience it is clear that an essential methodology for stabilizing eroding sandy beaches must be established. **Fig. 22** shows an example of the reduction process of the river delta on the Niigata coast as hindcast by the long-term shoreline prediction model (Yamashita, Tsuchiya, Matsuyama and Suzuki[32]) in order to visualize the large scale coastal behavior. Although neither the entire area of the river delta is covered nor the influence of ground subsidence on shoreline retreat included, it can be seen that due to lack of sediment input from the Shinano River severe beach erosion has taken place near the river's mouth and has extended widely down coast. However, if further calculation is made down coast, theoretically a deposition area may appear there. On the basis of the large scale shoreline change respected by the reduction process of the Shinano River delta, a methodology for beach erosion control is proposed in which a series of static stable sendy beaches are to be constructed from the river's mouth to the depositional point near the Shinkawa fishing harbor, in which beach length and spacing change gradually in relation to the preservation and utilization of hinterland areas. A methodology of the formation of sandy beaches has been proposed as a

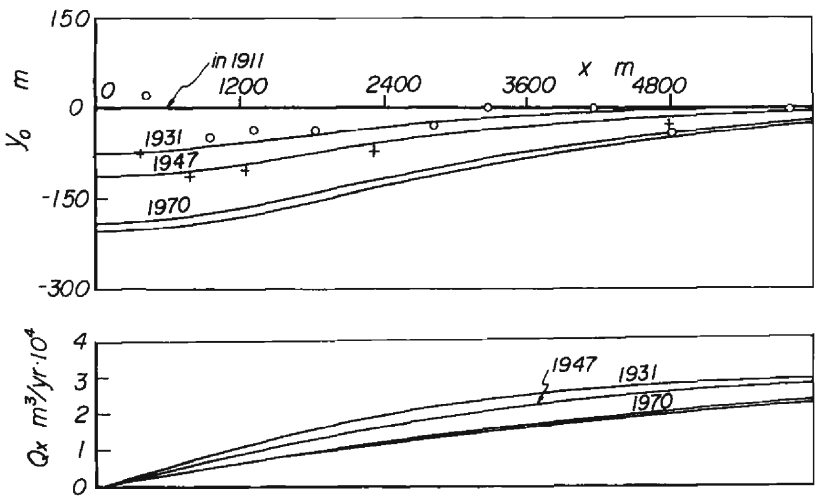


Fig. 22. Hindcast long-term shoreline change for the Niigata coast facing the Japan Sea.

practical means of stabilizing sandy beaches (Tsuchiya, Yamashita and Izumi[35]).

4. Conclusion

Although many measures have been taken to control beach erosion, little has been accomplished for the long-term stabilization of eroding sandy beaches. An essential methodology for beach erosion control, based on the principle or background of sandy beach stabilization is greatly needed. In 1976, Silvester proposed a methodology for beach erosion control that uses a headland defense that forms static stable sandy beaches. It is based on coastal geomorphological knowledge about the natural sandy beaches of a ζ-shaped bay. In our joint investigations of the applications of headland defense to Japanese sandy beaches, I have been concerned with the theoretical background for the formation of stable sandy beaches, in particular their existence and plane configuration.

As two types of stable sandy beaches have been considered that are based on natural sandy beaches, the ordinary second-order differential equation for stable sandy beaches has been reduced from the set of equations for longshore sediment transport and continuity of shoreline change. The solution to the equation is determined by two boundary conditions, on the up and down coasts. This means that to control beach erosion by the formation of sandy beaches, only two boundary conditions for shoreline change are necessary, and that when the conditions are definite, a single stable sandy beach is formed by the predominant weve thereby stabilizing the sandy beach between the boundaries.

The solution of the plane configuration of a stable sandy beach has been obtained. It compares satisfactorily with the configuration of actual sandy beaches formed between the groins on a sand spit called Amanohashidate in Miyazu Bay.

On the basis of the theoretical background of a stable sandy beach and current knowledge of sedimentation cells and of the most effective beach for wave energy dissipation, a methodology for beach erosion control has been developed in which the total rate of longshore sediment transport is controlled. Two methodologies have been proposed and two practical applications for beach erosion control have been given to show the validity of these methodologies. In the first, in which beach erosion takes place due to a decrease in or lack of sediment sources and due to the construction of large coastal structures in order to form a sandy beach, beach erosion control by headlands has been used to preserve a natural pocket beach, Shirarahama, in Wakayama Prefecture (completed satisfactorily), as well as at the Jotsu–Ogata coast that faces the Japan Sea and at the Kuta and Nusa Dua beaches in Bali (the former is under construction and the latter have been partially completed). It also has been used at Amanohashidate, a sand spit in Miyazu Bay (already completed), and has been proposed for the Kaike coast that faces the Japan Sea. In these applications, the most suitable arrangement of headlands for creating stable sandy beaches was obtained from long–term shoreline predictions in relation to large scale coastal behaviour.

In the second case, in which beach erosion takes place as part of the reduction process of a river delta, theoretical prediction of shoreline retreat as the reduction process of a river delta has been made for obique wave incidence. The reduction process of a river delta on the Niigata coast was given to show large scale coastal behavior. Due to lack of sediment input from the Shinano River, severe beach erosion was shown to have taken place near the river's mouth and to have extended widely down coast. But, if calculations are made for areas further down coast, a depositional area may appear around the Shinkawa fishing harbor—as theoretically predicted. On the basis of the extensive scale of this shoreline change, the methodology for beach erosion control was found to be a series of static stable sandy beaches to be constructed from the river's mouth to the depositional point in which beach length and spacing change gradually.

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